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CAUSE OF THE PRELIMINARY REVERSE IMPULSE OF STORMS

E. H. Vestine and J. W. Kern

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PREFACE

This report is a product of the continuing study of particles and fields in space being conducted by the RAND Corporation under contract No. NASr-21(05) for the National Aeronautics and Space Administration.

The substance of this report was presented at the First Western National Meeting of the American Geophysical Union, December 27-29, 1961.

ABSTRACT

Atmospheric-current functions obtained for sudden commencements by Nagata and Abe, and by Jacobs and Obayashi, are analyzed. Electric-charge distributions in the ionosphere are deduced that could drive the part of the currents asymmetric about the geomagnetic axis. It is supposed, as an approximation, that only the Hall electric conductivity need be taken into account. The electric field at the equator is calculated, and compared with the observed local abnormal augmentation of the sudden-commencement field. Distortions of the outer magnetosphere that may give rise to the reverse impulse are discussed.

ACKNOWLEDGMENT

It is a pleasure to indicate our indebtedness to W. L. Sibley, who undertook the machine calculations used in this paper, and to Miss Louise Olds who assisted in other ways in its preparation.

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I. INTRODUCTION

Within the polar cap of the earth, as well as in lower latitudes, a magnetic signal precedes the sudden commencement of storms. The lower latitude signals are usually attributed to the interaction of a solar stream with the magnetosphere, following Chapman and Ferraro (1931, 1932, and 1933), Chapman (1960), Ferraro (1960). The propagation of the magnetic signal is probably hydromagnetic as more specifically indicated by Dessler and Parker (1959). Presumably, the polar cap signals are due to atmospheric currents (Nagata and Abe, 1955). That dumping of auroral particles into the polar cap is responsible was suggested by Vestine et al. (1947), and Forbush and Vestine (1955). This possibility is further considered here on the basis of a dumping mechanism proposed by Kern (1961) and more recently discussed by Vestine (1962).

Sugiura (private communication) has pointed out that the preliminary reverse impulse (PRI) may be interpreted as an initial hydromagnetic effect. This possibility, discussed here, is interesting and far from simple, as the initial interactions at the contact surface between magnetosphere and solar stream are quite unknown. It is also apparent that hydromagnetic propagation of such an interaction through the magnetosphere is rather complicated (MacDonald, 1961).

For these early stages of a storm, current-flow patterns are difficult to construct. First, sufficient stations are ordinarily available only during special years, and second, other background disturbances obscure the SC-signal. Since PRI's occur at other hours (Matsushita, 1957), considerable variability in current pattern is expected. Despite these limitations, some current-flow patterns have been constructed.

The present paper examines two equivalent ionospheric-current systems derived for magnetic disturbances associated with the onset of geomagnetic storms. The first current system is that given by Nagata and Abe (1955) for preliminary reverse impulse at 6h 25m GMT, May 29, 1933. The second current system is for the polar part of the averaged sudden commencement (SC) as given by Jacobs and Obayashi (1956). Electric-charge distributions which would drive these current systems are derived from potential analyses.

Finally, the interaction between an approaching solar stream and the magnetosphere is discussed. It is shown that a simple extension of the Chapman-Ferraro theory can provide the observed polar charge distributions.

The mechanisms here described for the PRI field and polar portions of the SC field are distinctly different. Both, however, relate directly to the compression of the magnetosphere by a solar stream. The PRI is ascribed to the dynamics of compression, and is purely a transient effect. The polar portion of the SC field is ascribed to the production of an asymmetric distribution of energetic trapped particles by compression of the magnetosphere on the side of the earth toward the solar stream. Such an asymmetric distribution of trapped particles has been discussed by Fejer (1961). For the purpose of the present paper, the compression of the magnetosphere is regarded as adiabatic.

II. CURRENT SYSTEMS FOR THE PRELIMINARY REVERSE IMPULSE AND SUDDEN COMMENCEMENT FIELD

Figure 1 shows atmospheric-current flows deduced by Nagata and Abe for the preliminary reverse impulse of the sudden commencement of May 29, 1933. The current is most concentrated across the polar cap, where it flows roughly away from the 9 a.m. local time meridian. A rough estimate, based on current arrows shown, gives the total current to be about 5000 emu. A representation of Fig. 1 in terms of a current function J (of course only roughly estimated) is shown in Fig. 2.

The shown current effect precedes the main hydromagnetic signal which tentatively would be simulated by a current flow from east to west around parallels of magnetic latitude. But another asymmetric field pattern emerges if the main sudden-commencement field is averaged around parallels of magnetic latitude and subtracted from the main SC field. This was done for the average of a number of SC's by Jacobs and Obayashi (1956) and is shown in Fig. 3. It will be seen that the current flow across the polar cap is similar to that of Fig. 2, but reversed in direction. So the interesting question again arises as to whether or not, in view of the localised polar field, dumping of charges now simultaneously accompanies the main hydromagnetic SC signal, rather than precedes it as before.

The charge distributions required to drive the currents of Figs. 2 and 3 will be estimated next.

III. POTENTIAL ANALYSES OF THE ASYMMETRICAL SC-FIELDS

The current functions represented in Figs. 2 and 3 were fitted at 10° intervals of latitude and longitude by a spherical harmonic series. A code for an IBM-7090 computer was available which provided coefficients to degree $\underline{n}$ and order $\underline{m}$ up to 12. It may be appropriate, before describing the results, to give a few general remarks on the analysis.

The ionospheric-current systems are assumed here to be driven by dumping of charged particles along magnetic field lines. The current systems are long in duration compared to the relaxation times for charge excesses in the ionosphere. Thus the electric fields associated with the currents must be maintained by <u>continuous</u> discharge of protons and/or electrons to the ionosphere. For a steady-state current system, the electric fields can be associated with steady-state charge distributions in the ionosphere. Such distributions of excess charge will undergo continuous loss due to various dissipative mechanisms and must be continually replenished from some source of charged particles.

Here a steady-state charge distribution will be taken as associated with the ionospheric-current systems. This charge distribution can be conveniently regarded as confined to a thin spherical sheet. The electric field of the charge distribution will drive currents which lead to the magnetic perturbations associated with the preliminary reverse impulse and the field of the sudden-commencement polar disturbance. The electric field in the ionosphere can be derived from a scalar potential V_e. If the charge distribution is regarded as confined to a spherical shell, and the location of the charge distribution is at a height in the ionosphere which is different from the height of maximum conductivity, then the scalar potential at this height of maximum conductivity must satisfy Laplace's equation. That is

$$\nabla^2 V_e = 0 \tag{1}$$

If then V_e at the point (r, θ, φ) is expressible in terms of surface spherical harmonics $Y_n(\theta,\varphi)$ of degree n, where θ is the colatitude, φ the longitude, and a the radius of the shell of charge below the E-region, one may write

$$V_e = \sum_{n=0}^{\infty} \frac{a^{n+2}}{r^{n+1}} Y_n(\theta,\varphi) \tag{2}$$

where

$$Y_n(\theta,\varphi) = \sum_{m=0}^{n} a(A_n^m \cos m\varphi + B_n^m \sin m\varphi) P_n^m$$

The radially integrated surface-charge density is

$$\sigma(\theta,\varphi) = \sum_{s=0}^{\infty} G\ Z_s(\theta,\varphi) \tag{3}$$

where G is a constant. Since

$$Y_n(\theta,\varphi) = \frac{4\pi}{2n+1} Z_n(\theta,\varphi) \tag{4}$$

$$\sigma(\theta,\varphi) = G\sum_{n=0}^{\infty} \frac{2n+1}{4\pi} Y_n(\theta,\varphi) \tag{5}$$

If a current results due to V_e, it will give rise to a current function J defined at a point P as the total current flowing from left to right across a line joining P to an origin O in the surface of the current sheet. If J_x, J_y are the south and east components of current

$$J_x = \frac{\partial J}{r \sin \theta \, \partial \varphi} \quad , \quad J_y = - \frac{\partial J}{r \partial \theta} \tag{6}$$

Moreover

$$J_x = k_{xx} E_x + k_{xy} E_y$$
$$J_y = k_{xy} E_x + k_{yy} E_y \tag{7}$$

where k_{xx} is the electric conductivity associated with an electric field E_x driving a current in the direction x.

If we take $k_{xx} \sim k_{yy}$, $k_{xy} = k_{yx}$ as k_1 and k_2, respectively,

$$J_x = k_1 E_x + k_2 E_y$$
$$J_y = - k_1 E_y - k_2 E_x \tag{8}$$

where k_1 and k_2 are functions $k_1(\theta,\varphi)$ and $k_2(\theta,\varphi)$, respectively.

Since from Eq. (2)

$$V_e = \sum_{n=0}^{\infty} \frac{a^{n+2}}{r^{n+1}} Y_n (\theta,\varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} \frac{a^{n+2}}{r^{n+1}} (A_n^m \cos m\varphi + B_n^m \sin m\varphi) P_n^m$$

and

$$E_x = - \frac{1}{r} \frac{\partial V_e}{\partial \theta} \, , \quad E_y = - \frac{1}{r \sin \theta} \frac{\partial V_e}{\partial \varphi}$$

one can write Eq. (8)

$$J_x = - \frac{k_1(\theta,\varphi)}{r} \frac{\partial V_e}{\partial \theta} - \frac{k_2(\theta,\varphi)}{r \sin \theta} \frac{\partial V_e}{\partial \varphi}$$
$$J_y = \frac{k_1(\theta,\varphi)}{r \sin \theta} \frac{\partial V_e}{\partial \varphi} + \frac{k_2(\theta,\varphi)}{r} \frac{\partial V_e}{\partial \theta} \tag{9}$$

Since J_x, J_y are known from geomagnetic data, as are also k_1, k_2 to a degree of approximation from ionospheric data, E_x and E_y may be found, and hence $\sigma(x,y)$.

It should be noted that Eq. (8) assumes no current flow occurs normal to the current sheet.

According to Baker and Martyn (1953), in the lower E-region, k_2 is at least 10 times larger than k_1 in the range of geomagnetic latitude 20° to 90° north or south. Hence, as a first approximation subject to later improvement,

$$
\begin{aligned}
J_x &= - \frac{k_2(\theta,\varphi)}{r \sin \theta} \frac{\partial V_e}{\partial \varphi} \\
J_y &= \frac{k_2(\theta,\varphi)}{r} \frac{\partial V_e}{\partial \theta}
\end{aligned}
\tag{10}
$$

Furthermore, if it be noted that k_2 varies slowly with geographical longitude with total variation by a factor of 2, say, and less than a factor of 10 from day to night, an additional approximation gives (writing $k = k_2$)

$$
\begin{aligned}
J_x &= - \frac{k \, \partial V_e}{r \sin \theta \partial \varphi} \\
J_y &= \frac{k}{r} \frac{\partial V_e}{\partial \theta}
\end{aligned}
\tag{11}
$$

from which it appears the functions V_e and J are similar in form if r does not differ much from a. In fact, we may be led to write $J = A\, V_e$ so that, from (2) and (11), $A = - k$ and

$$
J = - k \sum_{n=0}^{\infty} \frac{a^{n+2}}{r^{n+1}} Y_n(\theta,\varphi) \tag{12}
$$

Since J can be found from the data, the vertically integrated charge inequality will be given by

$$\sigma(\theta,\varphi) = -\frac{1}{k} \sum_{n=0}^{\infty} \frac{2n+1}{4\pi ac^2} Y_n(\theta,\varphi) \tag{13}$$

where the constant G in Eq. (5) has taken the value $-\dfrac{1}{kac^2}$.

Introducing the value of $Y_n(\theta,\varphi)$

$$\sigma(\theta,\varphi) = -\frac{1}{k} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \frac{2n+1}{4\pi ac^2} (A_n^m \cos m\varphi + B_n^m \sin m\varphi) P_n^m \tag{14}$$

where A = - k.

It may also be noted that since

$$V_e = -\frac{1}{k} J \tag{15}$$

$$E_x = X_e = -\frac{1}{a} \frac{\partial V_e}{\partial \theta} = \frac{1}{ak} \frac{\partial J}{\partial \theta} \tag{16}$$

$$E_y = Y_e = -\frac{1}{a \sin\theta} \frac{\partial V_e}{\partial \varphi} = \frac{1}{a\, k \sin\theta} \frac{\partial J}{\partial \varphi} \tag{17}$$

$$E_z = Z_e = -\frac{\partial V_e}{\partial a} = \frac{1}{k} \sum_{n=0}^{\infty} (n+1) Y_n(\theta,\varphi) \tag{18}$$

IV. CALCULATIONS OF CHARGE DISTRIBUTIONS

The ionospheric electric conductivity varies with geographical location and time of day. From the preceding discussion, based on Baker and Martyn's results, a value for the vertically integrated Hall conductivity per cm^2 column of the ionosphere of about 5×10^{-8} emu-cm may be appropriate. The height of the current flow will be about 100 km giving the radius of the spherical shell as 6470 km. If displacement currents are neglected, the integrated charge densities required to drive the currents of Figs. 1 and 2 are shown in Figs. 3 and 4. In the computations all zonal harmonics (terms for which the order $m = 0$) which were obtained in the analysis of Figs. 1 and 2, have been deleted. Such terms are ascribed here to a hydromagnetic pressure increase associated with the SC field. The horizontal components of the associated electric fields are orthogonal to the contours of constant-charge density shown in the figures.

V. THEORY OF PRI

The world-wide magnetic changes which comprise the preliminary reverse impulse can be interpreted in several ways. In the preceding sections, emphasis was placed on the construction of an ionospheric current system which would produce the observed magnetic-field perturbations. Wilson and Sugiura have analyzed many SC and PRI disturbances and find simultaneous changes in the amplitude and direction of the perturbation vector of the disturbed magnetic field. They then interpret the PRI field as the initial phase of a continuous hydromagnetic perturbation which is propagated from the region of interaction of the magnetosphere and a solar stream (Wilson and Sugiura, 1961). In this interpretation, the PRI and SC fields are distinguished only by a nomenclature resulting from observations of only one component of the perturbation field. The PRI field is that portion of the perturbation in which the horizontal component of the magnetic field is decreased. The SC field then is that portion of the perturbation for which the horizontal component of the field is increased. If the total perturbation vector is examined, a continuous change of direction is found. Sugiura interprets this change as a rotation of the perturbation vector in a hydromagnetic wave propagating along magnetic-field lines.

Particle bombardment of the ionosphere is, however, associated with the magnetic-field changes described above. Thus, the discharge of particles from a plasma trapped in the portion of the magnetosphere interacting with an approaching solar stream becomes of interest.

The velocities usually associated with an approaching solar stream are of the order of 10^8 cm/sec (Martyn, 1951). This is at least an order of magnitude higher than the Alfvén velocity for the magnetosphere at distances greater than a few earth radii (MacDonald, 1961). This fact leads to the conclusion that a strong hydromagnetic shock wave will form in the region in front of an approaching solar stream. The geomagnetic field will be excluded from the interior of the solar stream by currents flowing in its face (Chapman and Ferraro, 1931 and later). Thus the geomagnetic field will be swept up in front of the solar stream. Protons and electrons trapped in the distant geomagnetic field will also be swept up into a transition region between the undisturbed geomagnetic field and the interface between the magnetosphere and the solar stream, in which the plasma density and the magnetic-field intensity undergo a large increase. The Alfvén hydromagnetic-wave velocity in this region will also be higher. Thus a hydromagnetic shock wave can be anticipated which travels in front of the solar-stream interface. The transition region is therefore confined between this hydromagnetic shock front and the front of the approaching solar stream. If the velocity of the shock front is U and the velocity of the plasma in the transition region behind the front is u, and if the density of the plasma in the undisturbed portion of the magnetosphere is ρ_1 while that behind the shock front is ρ_2, then $\rho_2(U - u) = \rho_1 U$, by conservation of mass. Also $B_1/\rho_1 = B_2/\rho_2$, where B_1 and B_2 are respectively the magnetic fields in front of and behind the shock front (Cole, 1959). It follows that $\rho_1 = B_1\rho_2/B_2$ and

$$(U - u)\,B_2 = B_1 U \quad \text{or}$$

$$U(B_2 - B_1) = uB_2 \tag{19}$$

Thus the plasma in the transition region has a mass motion relative to the magnetic field in the transition region, and a polarization field E_2 can be anticipated which is given by

$$\mathbf{E}_2 = - \mathbf{u} \times \mathbf{B}_2 \tag{20}$$

If $\mathbf{u}$ is transverse to $\mathbf{B}_2$, $\mathbf{E}_2$ becomes simply $-uB_2$, or $E_2 = - U(B_2 - B_1)$. The duration of such a polarization field will be very nearly the time required for the solar stream to be stopped by the compression of the geomagnetic field. This will be about 50 secs from the time of first arrival of the solar stream at the boundary of the magnetosphere at a distance of about 15 earth radii. The velocity U of the hydromagnetic shock wave will be very nearly the same as that of the solar-stream interface, i.e., about 10^8 cm/sec. The difference in the magnetic fields B_2 and B_1 will depend on the Alfvén velocity in the transition region. At a distance of 10 earth radii, this difference might be of the order of 10^{-3} gauss. Thus the anticipated electric-field intensity will be about $10^8 \cdot 10^{-3} = 10^5$ emu. A time average for E_2 would give $\bar{E}_2 \sim 10^8 \cdot 10^{-4} = 10^4$ emu.

If projected along geomagnetic field lines into the polar region, the direction of this anticipated polarization field will be just that required to drive the PRI current. An alternative viewpoint is that of discharge of protons and electrons from the transition region in front of the advancing solar stream due to the production of magnetic-field gradients. Such gradients would be directed toward the region of maximum compression of the geomagnetic field. Components of the local magnetic-field gradient which are parallel to the interface between the solar stream and magnetosphere will lead to charge separation as discussed by Kern (1961) and more recently by Vestine (1962). It should be noted that because of the discrepancy between the solar-stream velocity and the velocity of propagation of hydromagnetic signals, such charge separation will be confined to the transition region between the hydromagnetic shock front and the solar-stream interface. Both of the above descriptions give the same direction for the polarization electric field in the ionosphere. Calculation of the currents involved for the charge-separation model is rendered difficult by a lack of detailed knowledge regarding the hydromagnetic transition region. The estimated value of E_2 is in reasonable agreement with the ionospheric electric fields estimated from the PRI current system of Nagata and Abe (1955). The location of the electric field driving the PRI current system would be predicted by the foregoing argument to be close to the geomagnetic dip pole on the sunward side of the earth. Near this point the PRI ionospheric currents would be anticipated to be directed toward the approaching solar stream.

VI. THEORY OF POLAR-IONOSPHERIC PORTION OF THE SC EQUIVALENT CURRENT SYSTEM

In describing the development of the PRI current system, Sec. V introduced the notion of a transition region of higher plasma density and magnetic-field intensity in front of an approaching solar stream. This notion can be extended to the period following, when the earth's magnetosphere is confined to a cavity in the solar stream. An equilibrium cavity will be formed within minutes after the solar-stream face has by-passed the earth, provided trapped particle effects on the geomagnetic field are neglected. During this period, the hydromagnetic pressure of the solar stream is communicated to the earth. This hydromagnetic pressure is the central feature of the initial phase of a magnetic storm, and has been discussed at length by many authors. Here attention will remain focused on inferred ionospheric-current systems, as in the perturbation-field analysis of Sec. III.

Section V indicated that the plasma trapped in the outer magnetosphere prior to the arrival of a solar stream would be compressed ahead of the solar stream. Possible non-adiabatic effects may be associated with this transition region. In the following discussion, it will be assumed that the compression is adiabatic, and hence that the magnetic moments μ of individual protons and electrons are constant. Also the plasma density ρ will be taken as inversely proportional to the magnetic-field intensity B, i.e., $B_1/\rho_1 = B_2/\rho_2$. (This is exact only for a two-dimensional magnetic-field geometry in which magnetic-field lines are straight and parallel.) Now the magnetic moment $\mu = W_\perp/B$, where $W_\perp$ is the kinetic energy of a proton or electron transverse to the magnetic field B. It can be shown, using the expressions for ρ and μ, that the energy density for the plasma varies inversely as the magnetic-field energy density $B^2/8\pi$ during an adiabatic compression. That is,

$$\rho_2 W_2/\rho_1 W_1 = B_2^2/B_1^2 \tag{21}$$

where ρ_1 and ρ_2 are the densities before and after the compression, W_1 and W_2 the corresponding particle energies, and B_1 and B_2 the magnetic-field intensities before and after the compression. Thus a compression of the magnetosphere on the sunward side of the earth will lead to increased plasma energy densities. It should be noted that for an adiabatic compression, such as that assumed here, the particles can be identified with particular field lines. Hence the particle energy densities associated with field lines conjugate to the earth's polar regions will be increased in the same ratio as, say, the minimum magnetic-field-energy densities along such field lines. For field lines originating near the geomagnetic dip poles, this change can obviously be quite great.

The plasma compressed into the cavity from the sunward side of the magnetosphere by an approaching solar stream will thus undergo an increase in energy density. Further, the distribution of this energized plasma will not be symmetrical. That is, the compressed plasma will be distributed in only the sunward portion of the cavity. It is easy to see that energy density gradients may exist which are not parallel to the local geomagnetic-field gradients. This is the situation discussed by Kern (1961 and 1962) and also by Chamberlain (1961) as the condition for polarization of a trapped plasma and for discharge of protons and electrons to the atmosphere. Fejer (1961) has discussed the current systems which would be associated with an asymmetrical ring current. The configuration of the energized plasma on the interior of the cavity can be described in this manner. Fejer shows that, for this geometry, the polar portion of the SC equivalent current system follows from eastward drift of electrons and westward drift of protons. It should be noted that here only an adiabatic compression is assumed. In this case, the duration of the asymmetric distribution of trapped particles corresponds to the duration of the cavity. Termination of the solar stream would lead to a return to the pre-storm plasma and field distribution. The plasma density distribution would be modified by $E \times B$ drifts during the period of compression. It is interesting to speculate that such modification could contribute to observed distributions of aurora and polar-electrojet current systems.

No mechanism appears available to bring about the general reduction of the geomagnetic field associated with the main phase of a geomagnetic storm while the cavity is in existence. Injection of particles from the solar stream while the cavity is in existence has been used by some authors to account for the main phase. Non-adiabatic acceleration of plasma already trapped in the magnetosphere by the hydromagnetic shock wave might account for a main-phase ring current. Such acceleration has been discussed by Dessler, Hanson, and Parker (1961) in connection with the main-phase ring current. The above discussion suggests that the location of the inner boundary of the ring current might correspond to the region conjugate to the auroral zone simply because the magnetic-field-energy density inside this region exceeds the energy density of solar streams. Non-adiabatic "heating" of trapped protons by shock waves would thus be restricted to the outer portion of the magnetosphere. Hence the auroral zone may represent the inner boundary for the penetration of shock waves driven by solar streams.

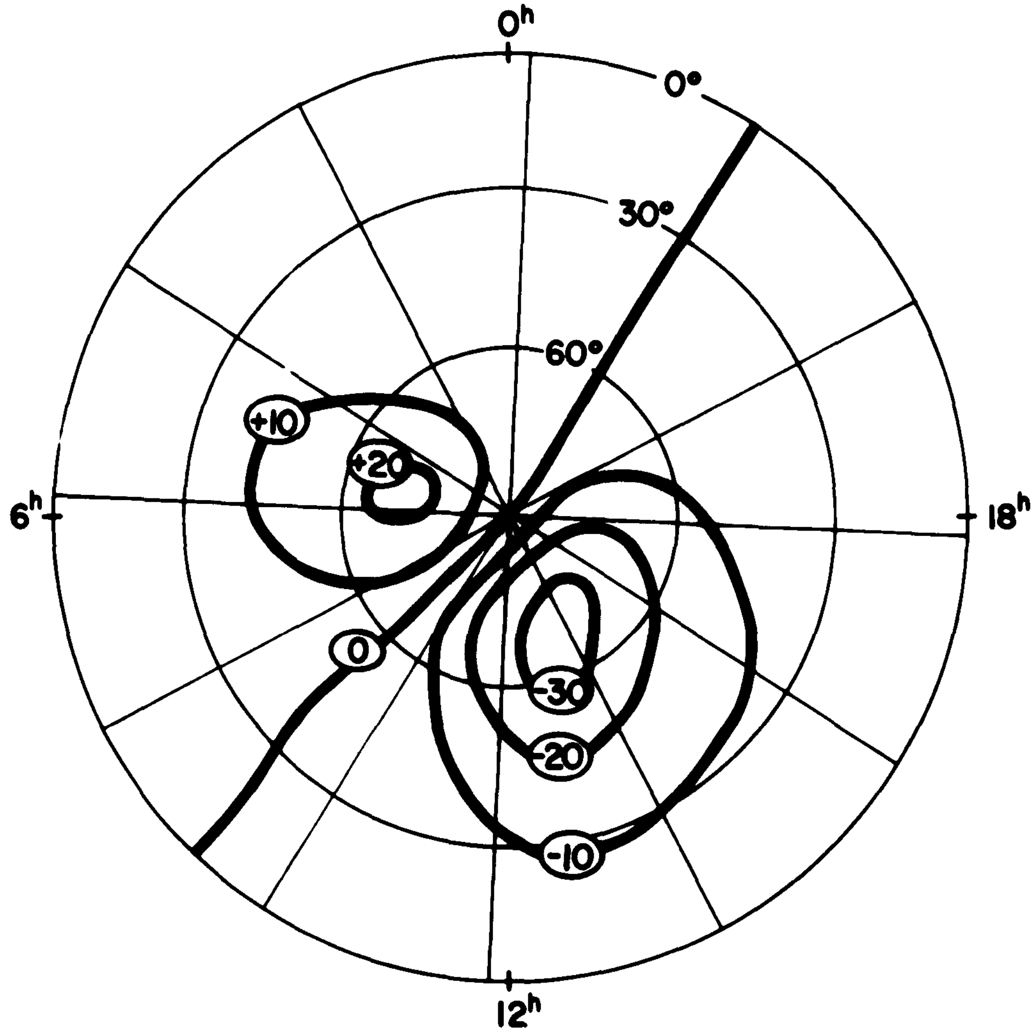

Fig. 1 — Current function J, case I, in units of 100 emu, estimated from data of Nagata and Abe for preliminary reverse impulse at $6^h 25^m$ GMT, May 29, 1933

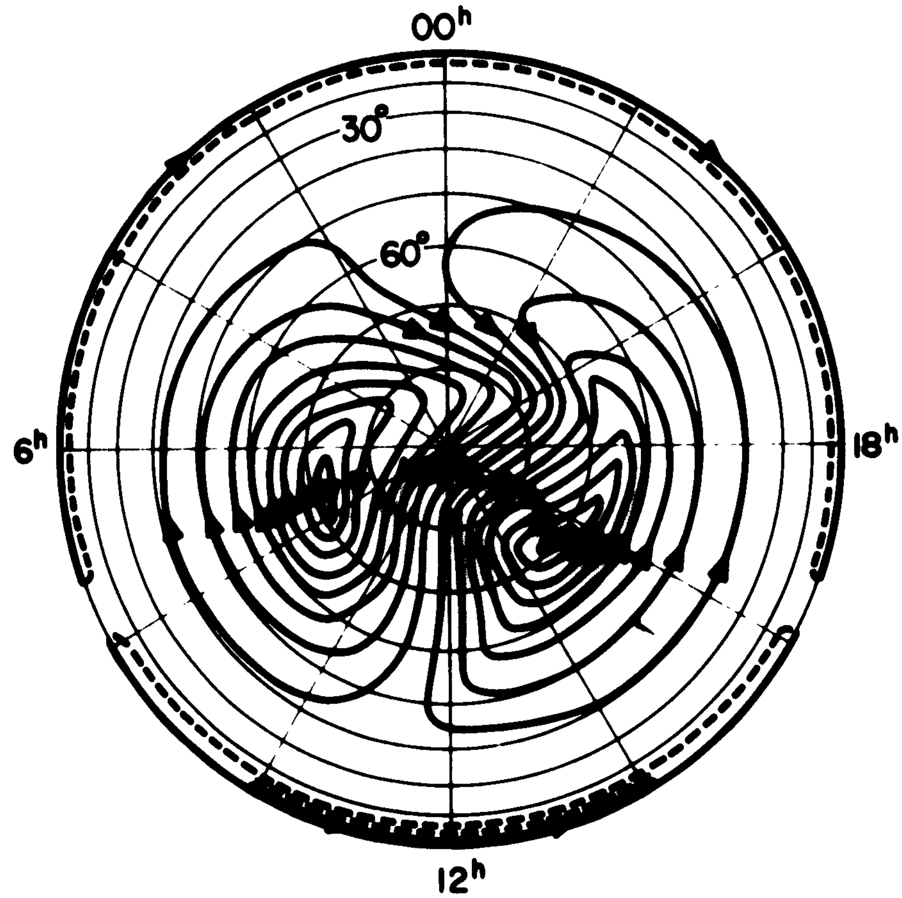

Fig. 2 — The electric current system corresponding to the nonsymmetrical part of the sudden-commencement field. Current of 10,000 amperes flows between adjacent stream lines

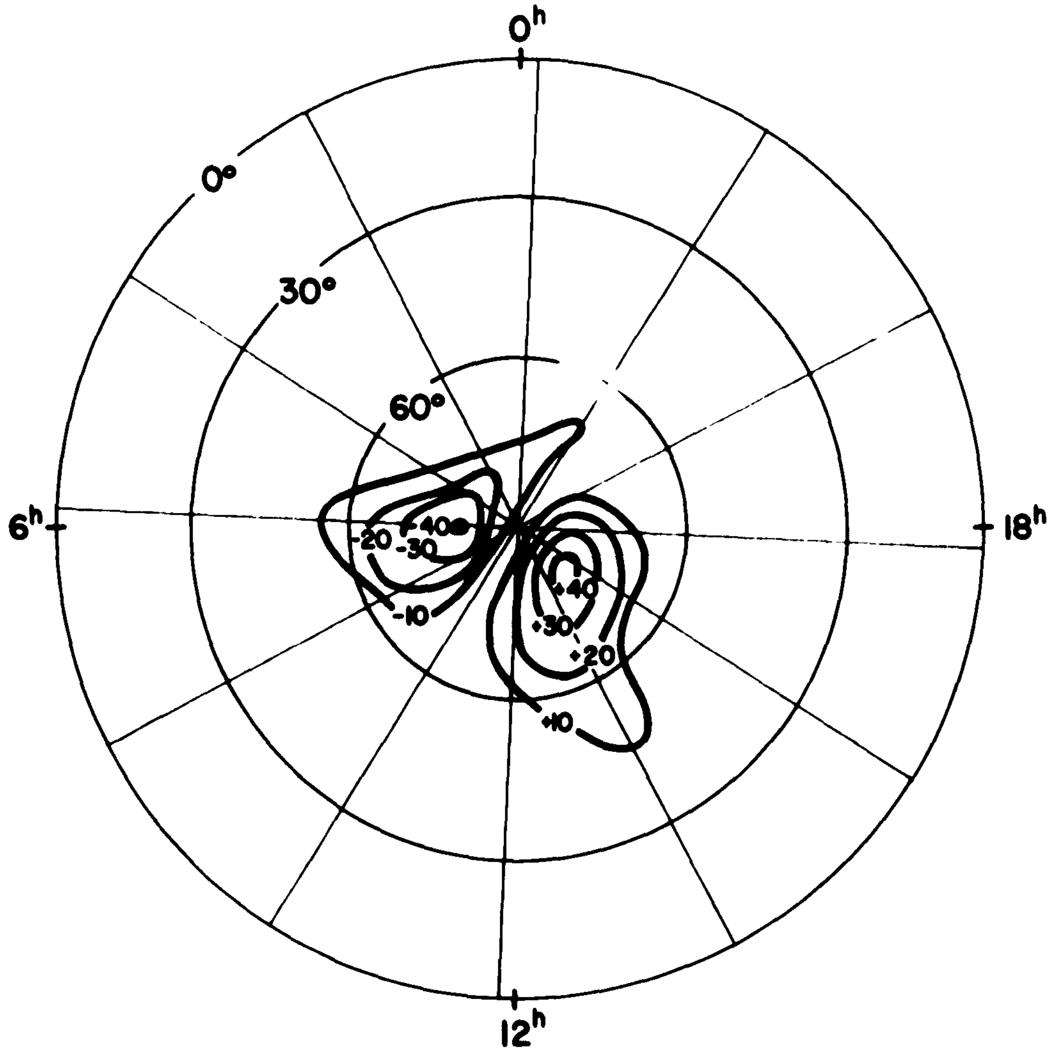

Fig. 3—Calculated number of excess charges per unit vertical column, σ, for preliminary reverse impulse at $6^h\ 25^m$ GMT, May 29, 1933

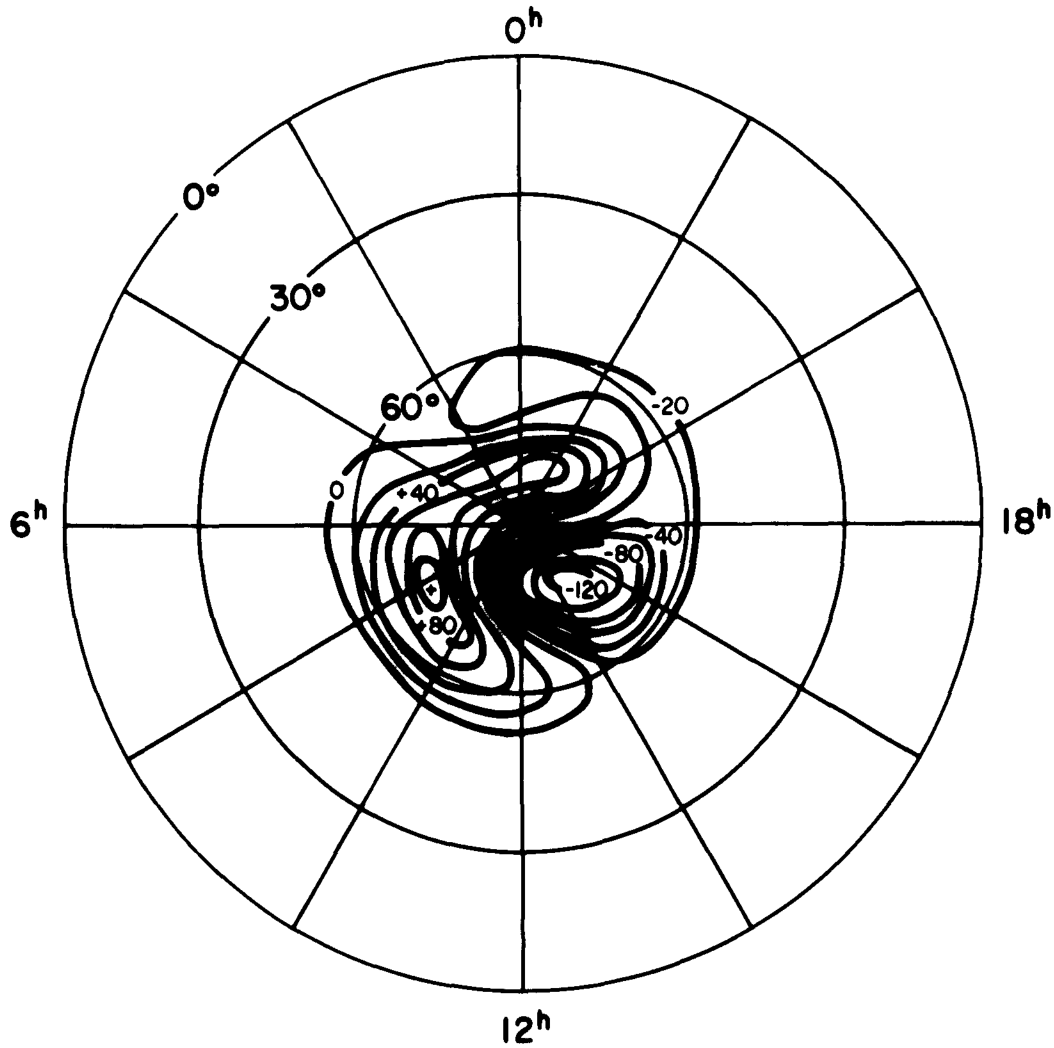

Fig. 4 —Calculated number of excess charges per unit vertical column, σ, for the nonsymmetrical part of main SC field. Northern hemisphere

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